Hybrid Satellite/Terrestrial Personal and Mobile Communications Research at JPL

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1. INTRODUCTION

This paper summarizes JPL's current efforts in mobile satellite communications. The work falls into two categories: Advanced Systems Work and Laboratory and Field Experimentation. The former looks at issues in PCS integration and interoperability. The latter utilizes the ACTS Mobile Terminal (AMT) to collect experimental data on mobile satellite communications.

2. ADVANCED SYSTEMS WORK

2.1 PCS Integration and Interoperability

In January 1995, JPL sponsored a workshop to discuss issues of PCS integration and interoperability. The following sections describe the major topics which were discussed.

2.1.1 Satellite/PCS Reference Model

This work element was a review of current cellular and PCS reference models with recommendations for modifications and additions required for satellite operation. There are a variety of reference models under consideration in North American standards bodies which drive the manner in which PCS networks will be deployed, The goal is to review these architectures from the perspective of inclusion of satellite PCS service. Interfaces and components in these models which might affect the satellite service must be identified

2.1.2 Network Management Issues

A close integration of satellite and terrestrial PCS systems may require dual mode users to select both systems independently, automatically select one or the other, or hand-off from one to the other. Mobility management to support this will require either multiple mobility management systems that are coordinated, or a common mobility management system. This includes Home and Visitor Location Register (HLR/VLR) issues, privacy and authentication issues, and intersystem signaling issues (such as handover between systems and network interworking) to support various strategies.

2.1.3 *Common Service Definitions*

This work element creates common service definitions for satellite and terrestrial PCS systems and reviews their implications. Inherent in the expectation that satellite and terrestrial systems will interoperate is the assumption that some basic set of features will be commonly supported in both environments. Thus, it is necessary to identify the set of services and features that would make sense to hold in *common, e.g.,* Group 3 Fax. This, however, would require careful coordination of terminal interfaces, radio link protocols, and interworking functions. Service definition would include human interface, data services, and network services.

2.1.4 Common Vocoders

Vocoders for satellite PCS systems may require a distinctly different set of voice coding technology then the terrestrial PCS systems. It is likely, for example, that rates as low as *2400* bps will be required for low power, handheld units. The issues which need to be addressed include the technical requirements for satellite PCS vocoders that might require new technical solutions. In addition, rates and vocoder algorithms that are common with terrestrial systems need to be researched,

2.2 **Satellites in the NII and GII**

The National Information Infrastructure (NII) and the Global Information Infrastructure (GII) are platforms ‘interconnecting telecommunications and computer networks for the efficient creation and diffusion of useful information services at the national and global level. The NII/GII agenda represents a vision for future multimedia communication networks employing widespread application of information technologies to provide useful services across all sectors of life, from health care delivery to electronic commerce, and from information networking, and education, to manufacturing[1]. Satellites play a pivotal role in realizing the vision of NII/GII.

Fixed, mobile and broadcast satellite systems are already essential components of today’s infrastructure. In the past, satellite and terrestrial system providers have operated separate, largely independent and unconnected, communication networks. The need for cost-effective geographically ubiquitous accessibility, the proliferation of mobile communications services, and the ever-increasing demand for more reliable services (even in the event of a natural disaster) have changed this situation. The NII/GII is a case in point. A hybrid, terrestrial-satellite, architecture is required if the main promises of the NII/GII - geographical ubiquity, affordability, accessibility, and interactivity - are to be delivered.

3. LABORATORY AND FIELD IEXPERIMENTATION

3.1 The ACTS Mobile Terminal (AMT)

JPL has developed a proof-of-concept breadboard mobile terminal system to operate in conjunction with NASA's Advanced Communications Technology Satellite (ACTS) at K/Ka-band. The complete technical details and architecture of this terminal can be found in [2]. The AMT can be broken down into two broad divisions, namely, the baseband and microwave processors. The baseband processor consists of a speech codec, a modem and a terminal controller (TC). Also included as part of this setup, strictly for experimental purposes, is a Data Acquisition System (DAS). The elements of the microwave processor are: the IF Converter (IFC), the RF Converter (RFC), the antenna controller, and the antenna.

The TC controls the operation of the AMT. It contains the algorithms that translate the communications protocol into the operational procedures and interfaces among the terminal subsystems. For example, it executes the timing and handshake procedures for the interaction among the speech coder, modem, user interface, and any external device (i.e., data source or data sink) during link setup, relinquishment, or data rate change. The TC also has control over the operation of the IF and RF electronics. The TC, in addition, is responsible for providing the user with a system monitoring capability and supports an interface to the Data Acquisition System (DAS). Finally, the TC will support the test functions required during experimentation, such as bit stream generation and bit error rate (BER) calculations.

. The speech codec converts input analog speech signals to a compressed digital representation at data rates of *2.4*, *4.8*, and *9.6* kbps, with monotonically improving voice quality. The 2.4 kbps compression algorithm is the government standard LPC-10, the 4.8 kbps algorithm is the proposed CELP government standard, and at 9.6 kbps an MRELP algorithm is adopted. The codec is capable of interfacing to the Public Switched Telephone Network (PSTN). For example, the user at the mobile terminal can place a call to a telephone anywhere in CONUS. In the PCS experiment, the audio interface was used as an "order wire" to support coordination and management of the experiment activities.

In the land-mobile setup, data rate switches are performed upon command from the TC based on the rain compensation algorithm (RCA) information or upon user command. Data rate switching is performed with no user intervention and "on-the-fly" to have minimal impact on the continuity of the link.

Two different modems have been used as part of the AMT. The baseline AMT modem, designed in-house, implements a simple yet robust DPSK scheme with rate 1/2, constraint length 7 convolutional coding and interleaving. The performance specification for this modem is for a BER of 10^{-3} at an E_b/N_0 of 7 dB in AWGN. Further capabilities have been built into this modem to compensate for frequency offsets of up to 10 kHz with an additional performance degradation of only 0.5 dB. This modem is operational at 2.4, 4,8, and 9.6 kbps. The second modem that has been utilized as part of this setup is a commercially developed satcom modem that includes such features as coherent BPSK with convolutional coding, concatenated coding (Reed-Solomon), and interleaving. The performance specification for this modem is for a BER of 10^{-6} at an E_b/N_0 of 5 dB in AWGN. This modem is operational at data rates ranging from 9.6 kbps to 2.048 Mbps.

The vehicle antenna is the critical K/Ka-band technology item in the microwave processor. The design of this antenna called for a "passive" elliptical reflector-type to be used in conjunction with a separate high powered amplifier. Complete with a spherical radome, it stands approximately 5 inches in height, and is approximately 8 inches in diameter at its base, The antenna is fully tracking in azimuth, while manually positioned in elevation to one of five distinct settings.[1] Combined with a 10 Watt TWTA, this antenna system provides at least 32 dBW transmit EIRP on boresight. The 3 dB beamwidth is ± 9° in elevation and ± 6° in azimuth. Receive specifications for this antenna have been set at -5 dB/°K, once again on boresight.

The antenna pointing system enables the antenna to track the satellite for all practical land-mobile vehicle maneuvers. The antenna is mated to a simple, yet robust, mechanical steering system. A scheme wherein the antenna is smoothly dithered about its boresight by about a degree at a rate of 2 kHz is used. The pilot signal strength is measured through this dithering process, and is used to compliment the inertial rate sensor information. This information allows the antenna to track the satellite while experiencing a shadowing event of up to 10 seconds in duration.

Preceding (or following) the antenna, the RFC converts an IF signal around 3.373 GHz to (from) a 30 (20) GHz signal for transmit (receive) purposes. The IFC translates the signal between 3.373 GHz and a lower 70 MHz IF at the output/input of the modem. A key function of the IF converter is pilot tracking and Doppler pre-compensation (for the return communication link).

3.2 AMT Experiments

As part of the ACTS experiments program, JPL has been given the task of seeking out useful applications for K- and Ka-band mobile satcom and to further demonstrate these capabilities through ACTS and the AMT. To date, twelve different experimenters involving several different government agencies, U.S. industrial interests, and academia have been officially approved to experiment with ACTS and the AMT by NASA Headquarters and the ACTS Project Office at NASA LeRC. The experiments period began in December 1993 and will continue for at least two years through November 1995.

A summary of the mobile experiments is presented in Table 1. Many other experiments are still in the formative stage. Applications-oriented experiments

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[1] These five settings allow for complete elevation coverage of the continental United States.

and demonstrations in such areas as emergency medicine, personal communications (PCS), disaster recovery, military communications, telemedicine, direct broadcast, and satellite news gathering have been or will be demonstrated. Details on all of these experiments can be found in [31. Further explanations on aeronautical mobile applications for K- and Ka-bands may be found in [41.

Table 1: ACTS Mobile Experiments Summary

EXPERIMENT	PRINCIPAL INVESTIGATORS
Land-Mobile, Phase I	JPL
Emergency Medical	EMSAT Corporation
Secure Land-Mobile, Phase I	NCS
Comrn-on-the-Move	U.S. Army CECOM
Aero-X	NASA LeRC
Satellite/Terrestrial PCN	Bellcore
Satellite News Gathering	NBC
High Quality Audio Broadcast	CBS Radio, CCS
Telemedicine	University of Washington Medical Center
Land-Mobile, Phase II	JPL
Secure Land-Mobile, Phase II	NCS, JPL
Unmanned Ground Vehicle	ARPA

3.3 K/Ka-band Propagation Results

Propagation experiments at UHF (850 MHz) and L- (1.5 GHz) bands have quantified the shadowing and multipath interference effects for these bands [5,6,71. ACTS provides a stationary platform ideally suited to the measurement of mobile propagation effects at K-(2O GHz) and Ka-(30 GHz) bands. Field tests conducted during the first 7 months of 1994 using JPL's AMT provide channel characterization data for both the K- and the Ka-band channels.

The system configuration is illustrated in Figure 1.. The forward channel originated at the fixed station with a 29.634 GHz pilot tone. This pilot tone was received by ACTS, mixed to the downlink frequency of 19.914 GHz, and transmitted on the Southern California spot beam. The forward channel offered a composite C/N_0 of 55.63 dB-Hz and was the basis for the K-band results. The return channel originated at the AMT with a 29.634 GH z pilot tone which was uplinked to ACTS, mixed to 19.194 GHz, and downlinked to the fixed station. The available C/No on the return channel was 53.58 dB-Hz. The return channel formed the basis for the Ka-band results.

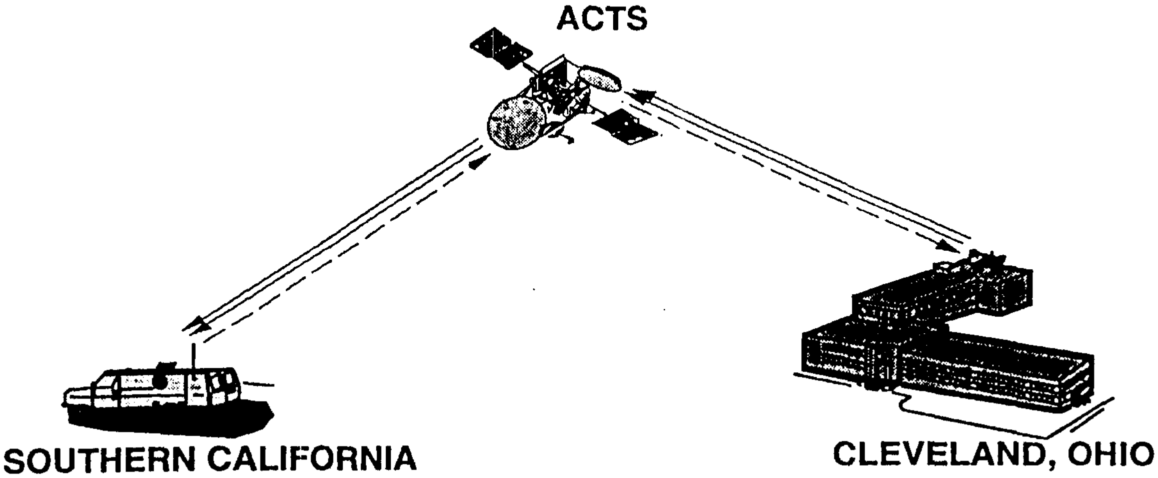


Figure 1: System Configuration

Data was collected in a variety of locations which may be broadly classified in three categories: lightly shadowed suburban, moderately shadowed suburban, and heavily shadowed suburban. These categories are somewhat subjective; however, the criteria used to label the road *were* as follows: 1) lightly shadowed roads had infrequent, partial blockage to the satellite, 2) moderately shadowed roads had occasional complete blockage to the satellite, and 3) heavily shadowed roads had frequent,. complete blockage to the satellite.

All tests were conducted in Southern California which does not experience large seasonal. variations. Therefore, the propagation effects due to foliage do not change throughout the year.

3.3.1 *Lightly Shadowed Suburban Environment*

Orange Grove Boulevard in Pasadena, California, is a broad, level thoroughfare with trees lining both sides of the road. The trees lining this route are primarily Southern Magnolia with Fan Palm and Date Palm trees spaced 50 meters apart. The road is laid out in a north-south direction. With the satellite to the south-east, the western most lane (right-hand, south bound lane) presented the best look-angle to the satellite. In this lane, the AMT antenna boresite to the ACTS line-of-sight path just barely skirted the tops of the Palm trees on the east, side of the road and, generally did not intersect the foliage of the Magnolia trees. This environment is characterized as lightly shadowed. A representative time series of the pilot power transmitted by the AMT and received at the fixed station is shown in Figure 2. The solid line represents the one second average of the 4000 samples. In addition, vertical dashed lines are displayed which connect the maximum and minimum values of the pilot power during the one second interval.

The statistics of the shadowing/fading are summarized by a histogram of the cumulative distribution of the pilot power received at the freed station. The histogram of the run shown on the left in Figure 2 is represented by the solid line on the right in Figure 2. Also shown is the histogram of the cumulative distribution of the pilot power received by the AMT (at K-band) at the same time (this is the dashed line). The solid line models the 30 GHz land mobile channel where it is seen that the 1% fade level for Ka-band is 8 dB. In other words, 1% of the time the pilot signal is worse than 8 dB below the reference level. This is essentially equal to that at K-band.

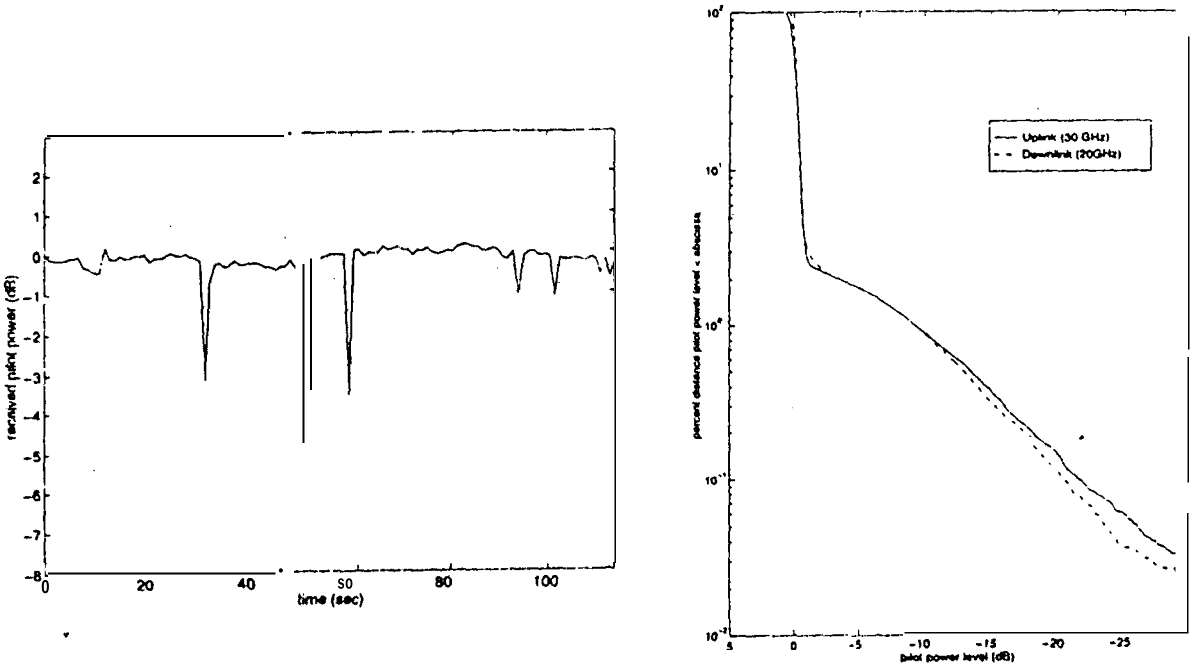


Figure 2: Lightly Shadowed Suburban Environment

3.3.2 *Heavily Shadowed Suburban Environment*

To obtain results from a heavily shadowed suburban environment, a route along Grand Avenue in Pasadena, was selected. Grand Avenue is a narrow two lane road with many turns and runs in a generally north-south direction. The road is lined with a heavy mixture of Coastal Live Oak, Southern Magnolias, and Holly Oak. In many places along the route, the tree canopies completely covered the road blocking any direct line-of-site path between AMT and ACTS. This environment is creates severe shadowing/fading as illustrated by the graph on the left in Figure 3. The statistics of the shadowing/fading are summarized by the histogram illustrated on the right side in Figure 3 where it is seen that the 1% fade level for Ka-band is well in excess of 30 dB (perhaps even as high as 45 dB). Results for the simultaneous return channel at K-band are also shown and are essentially equivalent.

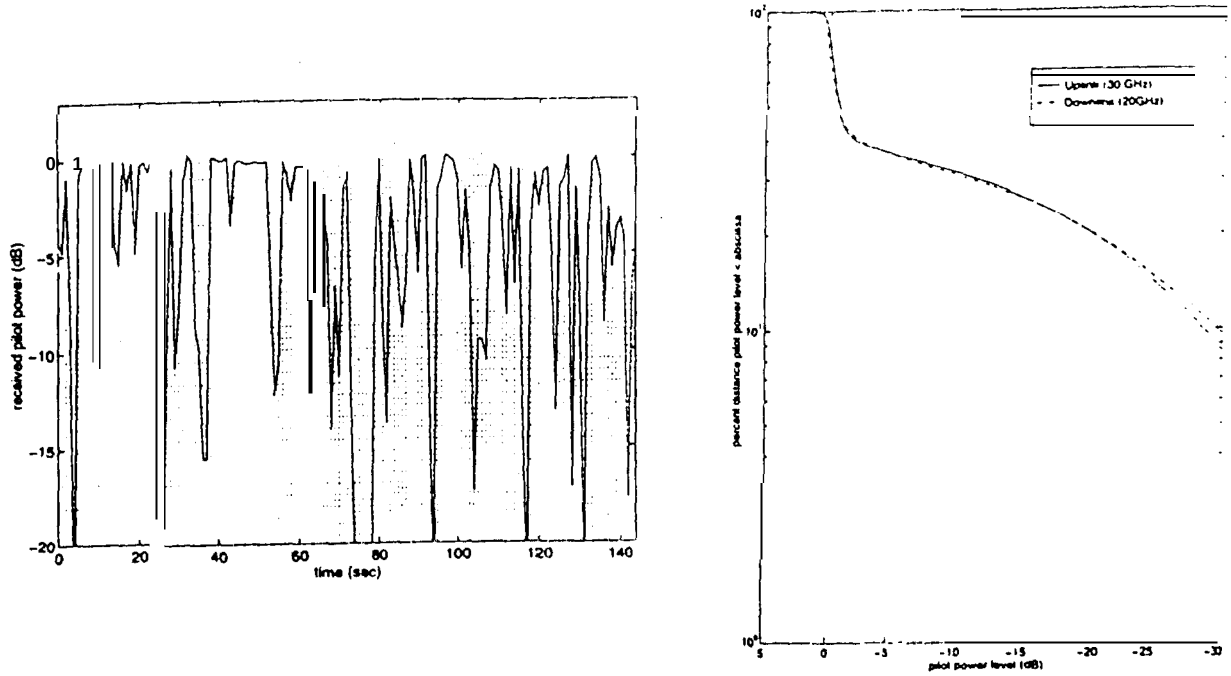


Figure 3: Heavily Shadowed Suburban Environment

3.3.3 Analysis

Each of the histograms illustrated in Figure 2 and Figure 3 displays the same characteristic shape. The slope between the reference level (O dB) and 2 dB below the reference level is steep. This is characteristic of Ricean fading which occurs when reflected copies of the transmitted pulse accompany the line-of-sight signal. This steep curve is followed by a "knee" which forms the transition between the Ricean characteristic and the shadowed fading characteristic. Shadowed fading contributes a shallower characteristic to the curve which indicates that the combination of signal blockage (shadowing) and multipath interference (sh adowed fading) is severe. The combination of these two characteristics suggests a "time share" between Ricean fading and shadowed fading as observed at L-band [5,6].

3.3.4 *Conclusions*

The results of the AMT Ka-band mobile propagation field tests show that the shadowing and fading processes are essentially identical for both K- and Ka-band frequencies and for the mobile transmitter and receiver. It may be possible to design link margins to provide reliable service for the lightly shadowed suburban environment at Ka-band. However, for areas with moderate and heavy shadowing, the link margin required to realize reliable communication with 99% availability is excessive (26 dB for moderate shadowing, and greater than 30 dB for heavy shadowing). An alternate approach would be to use shadowing/fading countermeasures (e.g., interleaved error control coding and antenna diversity). Such mitigation techniques, necessary for reliable K/Ka-band mobile communication within a suburban environment, are currently being considered within the NASA program.

3.4 Satellite-Enhanced Personal Communications Experiments

As an initial step in exploring the opportunities afforded by merging various networks, Bellcore and JPL conducted a series of experiments [8] to demonstrate the joint use of satellites and terrestrial networks in the delivery of personal communications services. The field trials were conducted during August 1994 and January 1995 in Los Angeles, CA and Morristown, NJ. During these trials, applications communicated over various combinations of networks including satellite, wireless packet data, the wired Internet, and the wired PSTN. The experiment goals fell into three categories: a) demonstrate the delivery of personal communications applications via satellite, b) demonstrate interoperability of satellite and terrestrial networks, and c) evaluate protocol mechanisms and parameters that make efficient use of wireless links.

These experiments% utilized Bellcore's Experimental Personal Communications System, NASA's Advanced Communications Satellite (ACTS), and JPL's ACTS Mobile Terminal (AMT). Figure 4 shows the experimental configuration involved in this series of experiments. The primary communication channel used for evaluation and measurements was that between Johndoe's PC and the Data Gateway via the satellite channel. The most demanding configuration was the connection from Janedoe's PC located in New Jersey, via the RAM Network, via the AMT van (effectively acting as a mobile base station), over the satellite, through the Data Gateway located in Los Angeles, and back over the Internet to New Jersey.

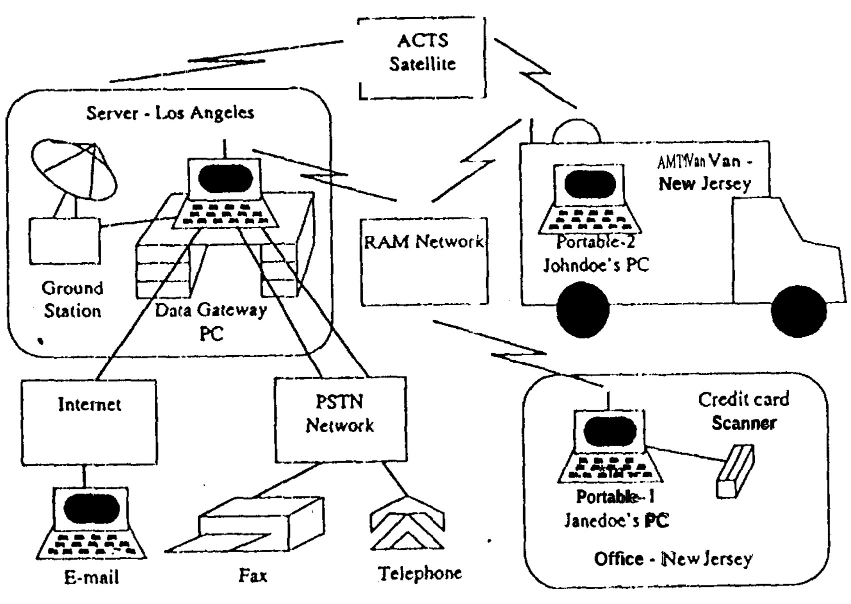


Figure 4: Satellite-Enhanced PCS Experimental Setup

An important question related to satellite-terrestrial interoperability is whether the data communications protocols can operate efficiently across multiple channels. Most protocols in use today (e.g., TCP/IP) have been optimized for wireline channels; their use over wireless networks presents significant new challenges. For error control an experimental transport protocol, called TPE, was used that was optimized for wireless networks. TPE frames the data *into* chunks *which* fit inside *a'* network packet. An integer number of chunks are combined to create a transport protocol data unit (TPDU). Figure 5 shows an example of how TPE segments an application PDU (APDU) into 5 data chunks. In addition, TPE adds 2 error detection (ED) chunks, because the application block was split into 2 Transport PDUS (TPDUs). TPE moves chunks directly to and from main memory - application data is never copied at the level of APDU or TPDU. In the field trials, TPE added 8 bytes/ packet for chunk header, put exactly one chunk into every packet. Further information on TPE can be found in [9].

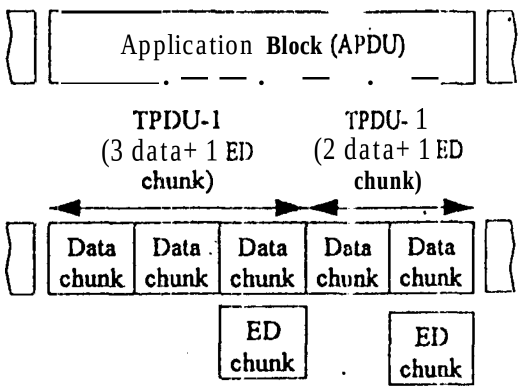
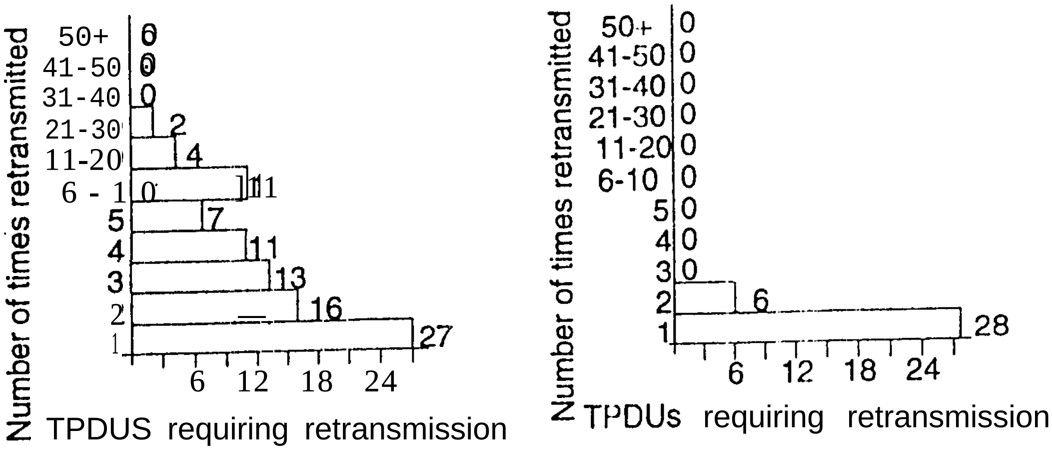


Figure 5: Segmentation of an Application Block into Data & Error Detection Chunks

During the Los Angeles anti Morristown field trials, experiments were conducted under varying channel conditions in order to characterize hybrid satellite-terrestrial personal communications. Both stationary and mobile tests were conducted at various signal strength levels. The error distribution for the mobile runs differed substantially from the error distribution for the stationary runs. Figure 6 shows that for the mobile tests, corrupted TPDUS often needed several retransmission, while for the stationary tests, most corrupted TPDUs only required a single retransmission.

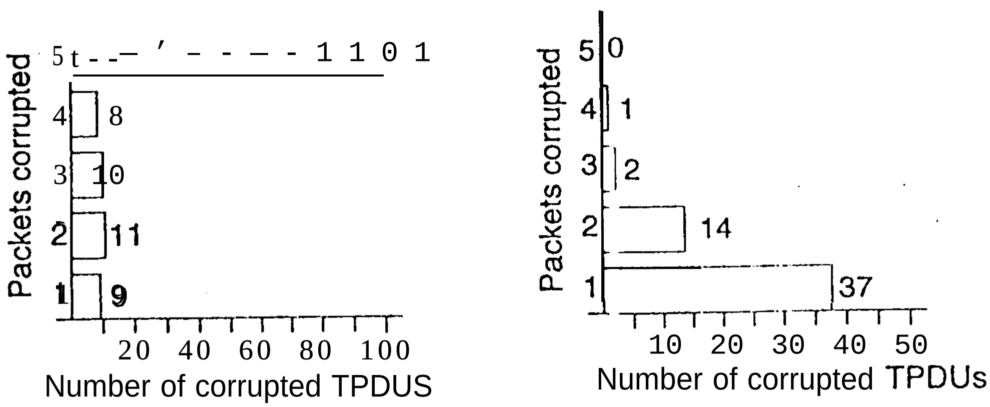


a) Mobile Test (with -15,000 192-byte TPDUs sent)

b) Stationary Test (with -15,000 192-byte TPDUs sent)

Figure 6: TPDU Retransmissions (using 8 packets per TPDU)

To investigate the error distribution further, the distribution of packet errors within a TPDU was graphed. Figure 7 shows results from experiments where each TPDU was composed of 5 small (24 or 32 byte) packets and statistics were collected on how many of these 5 packets were destroyed within corrupted TPDUs. The figure shows that for the mobile test, most corrupted TPDUs had all 5 packets destroyed. For the stationary test, most TPDUs lost only a one or two packets. In stationary tests with larger (128 and 256 byte) packets (not shown), most TPDUs lost only a single packet.



a) Mobile test with 24-bytes/packet (139 of -8000 TPDUs corrupted)

b) Stationary test with 32-bytes/packet (54 of -8000 TPDUs corrupted)

Figure 7: Packet Error Distribution (within a 5-packet TPDU)

As our results confirmed, the radio propagation environment is well modeled by a time-share between Rician and Rayleigh fading. It is critical, therefore, that wireless error control schemes work efficiently under both types of fading conditions. Mechanisms and parameters that work well under only one scenario will not provide robust service and will limit the range of useful operations.

The results confirmed earlier observations on the power of error control " mechanisms such as selective acknowledgment and chunk combining [9]. The results also demonstrate that dynamic algorithms are required to change the error control parameters.

4. ACKNOWLEDGMENTS

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